SOUTHERN CALIFORNIA COASTAL WATER RESEARCH PROJECT AUTHORITY

THEMATIC RESEARCH PLAN

FOR

STORMWATER BEST MANAGEMENT PRACTICES (BMPs)

Last revised May 2019

Table of Contents

Introduction

Wet- and dry-weather runoff in Southern California poses a particularly vexing challenge for the water-quality management community. During both wet and dry weather, contaminants wash off the land from across hundreds of square miles of urban, industrial and agricultural landscapes. Discharge of this contaminated runoff into receiving waters has been linked to microbial contamination in recreational surface waters (Marsalek and Rochfort 2004), excess nutrient loading that can trigger harmful algal blooms (Grigas et al. 2015), and increased toxicity that degrades ecological condition (Sebastian et al. 2015). Numerous regulatory and management programs have been implemented to reduce contaminant loading and mitigate the impacts of runoff on downstream aquatic ecosystems and on human health. But the diffuse nature of runoff has complicated management efforts to pinpoint and eliminate non-point sources.

For decades, SCCWRP has been facilitating research aimed at characterizing, monitoring and tracking the spread of runoff contamination through aquatic environments, and documenting downstream ecological impacts in coastal marine environments and other habitats. Building off this scientific foundation, SCCWRP is now increasingly shifting its focus to developing and evaluating management strategies, tools and insights for improving runoff water quality – an area known as best management practices (BMPs). SCCWRP's research spans the two main types of stormwater BMPs: (1) Structural BMPs, which include detention, retention, and treatment systems designed to capture, treat, and recycle stormwater to minimize adverse impacts on receiving water bodies. A structural BMP may use a combination of various physical, chemical, and biological processes to accomplish its design objectives. (2) Non-structural BMPs, which include source control and other priority program management options such as street sweeping or public education. SCCWRP is working to build a foundational understanding of both structural and non-structural BMP processes. SCCWRP's goal is to help inform the design, implementation and ongoing maintenance of BMPs across southern California – and ultimately, optimally reduce both pollutant loading and total runoff volumes. Especially as southern California's environmental management community prepares to invest billions of dollars on BMPs to manage runoff in the coming decades, SCCWRP is committed to helping its member agencies understand how implementing a certain BMP or a combination of BMPs can be expected to influence receiving-water quality over the long-term (Hager et al. 2018). These insights are critical to turning contaminated runoff in southern California into a beneficial-use resource.

Conceptual Model

SCCWRP's conceptual model for the Stormwater BMPs research theme centers around building a scientific foundation for understanding the sources and fates of stormwater and non-stormwater runoff, then using these insights to inform the development of effective BMP intervention that attenuate runoff pollutant concentrations and loads and that ultimately help improve receiving-water conditions. In the conceptual model (Figure 1), SCCWRP has placed all of the research areas that make up this research theme into six major categories that are fall into three major tiers: (1) Sources (Hydrology; Pollutant Source); (2) Fate (Watershed Processes; BMP Intervention); and (2) Effects (Stormwater Capture; Receiving Water Responses). Like most interdisciplinary research at SCCWRP, other SCCWRP research themes integrate within this conceptual model, including SCCWRP's Ecohydrology, Eutrophication, and Regional Monitoring research themes. Unlike these other research themes, however, this Stormwater BMPs research theme focuses on presenting all aspects of stormwater science and how they influence stormwater management.

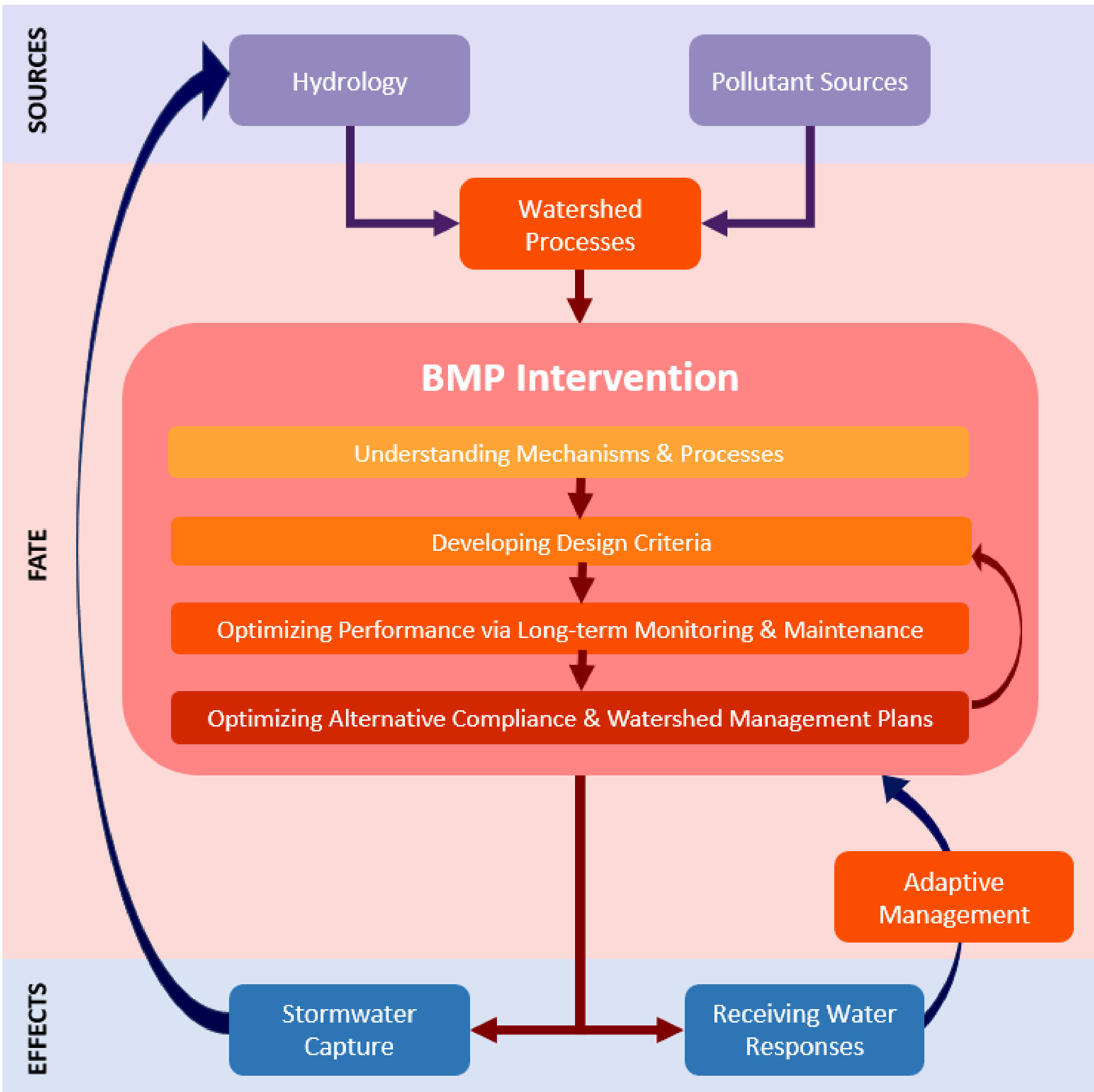

Figure 1. SCCWRP's Stormwater BMPs research theme is driven by the need for improved, cost-effective engineering solutions to address increasingly stringent regulations for stormwater discharge, as well as minimizing runoff impact on marine and fresh water bodies. Because of the progress that SCCWRP has made in the Sources and Effects tiers, SCCWRP is increasingly shifting its focus to the BMP Intervention area, which is broken into four sub-areas. The BMP interventions can be both structural and non-structural.

The three major tiers of SCCWRP's conceptual model are sources, fate and effects, with BMP intervention a part of the fate tier.

Sources

Hydrology: Changes in urban hydrology is a function of multiple factors, including growth in urban population, land use changes, new development, and climate (McGrane 2016). Hydrologic characterization of an urbanized landscape helps estimate the amount of runoff, direction of flow path, flow velocity, and peak flow to be controlled using stormwater BMPs (Fletcher et al. 2015, Bell et al. 2016). Changes in flow – also termed hydromodification – can lead to detrimental environmental impacts, such as flooding, increased erosion, increased pollutant loading, or all of these combined. Thus, understanding and characterizing hydrologic processes as well as predicting future hydrologic regimes are key to appropriate BMP sizing and design to meet long-term management objectives. Part of this challenge is a lack of well-established methods for input parameters to predict changes in urban flows (such as effective impervious area), which are critical for estimating how much precipitation runs off versus soaks into the ground (more impervious surface = more runoff). Overlaid upon changing urban hydrology are shifts in precipitation patterns due to climate change, an added complexity that further complicates efforts to select appropriate sizing criteria to achieve optimized stormwater BMP designs.

Pollutant Sources: Quantifying pollutant sources is a fundamental piece of the stormwater conceptual model. Knowing which pollutants come from which sources is essential for determining where and when source control options are best applied. When source control is not an option, quantifying each pollutant source is critical for knowing not just where to apply BMPs for treating runoff from each source, but also for ensuring that BMP planning, selection and design specifications are optimized for treating each source efficiently and effectively. The challenge with quantifying sources in stormwater runoff is the vast number of non-point sources across watersheds and the highly variable nature of pollutant source contributions during wet weather. Unlike wastewater where flow and concentrations are relatively stable, stormwater flows and concentrations in southern California can change by orders of magnitude within a one-hour timespan. Thus, research in this area must focus on pollutant source tracking that addresses post-storm evidence of receiving water contamination. Additionally, research must focus on the ability to address not just traditional stormwater contaminants (e.g., solids, nutrients, metals, bacteria, pesticides), but also emerging contaminants not routinely monitored (e.g., new pesticides, pathogens, cyanotoxins, endocrine-disrupting hormones).

Fates

Watershed Processes: Watershed processes play an important role in the movement of stormwater and non-stormwater runoff from its source to a BMP, and then from a BMP to its receiving water. These watershed processes influence the timing, velocity and total volume of flow, as well as which pollutants are mobilized, sequestered, and/or transformed. All these variables can dramatically influence BMP location, sizing and design features. Watershed processes become particularly important as stormwater managers emphasize infiltration as the preferred BMP method to reduce runoff flow and pollutant loading, while simultaneously storing runoff for later use, especially in a drought-prone region like southern California. Research in this portion of the conceptual model focuses on stormwater-groundwater interactions, as managers need to make informed decisions about what volume of runoff should be captured using infiltration BMPs without impacting the environmental flows necessary to maintain healthy biological communities in receiving streams and/or to determine what fraction of pollutant loading can be safely infiltrated without impacting groundwater quality.

BMP Intervention: BMP intervention is the focal point of SCCWRP's Stormwater BMPs research theme. Despite the importance of BMP intervention on the success of a stormwater management program, there is a surprising lack of scientific information on how structural BMPs work. This limits stormwater managers' ability to implement optimal strategies that ensure that the billions of dollars they will be investing over the next decades will result in improved water quality and restored beneficial uses. SCCWRP breaks this portion of the conceptual model into four sub-areas that encompass the different aspects of the stormwater BMP implementation program: (1) Mechanistic understanding of contaminants removal processes in stormwater BMPs; (2) Developing design criteria for stormwater BMPs; (3) Optimizing long-term BMP performance through monitoring and maintenance; and (4) Optimizing Alternative Compliance Pathways (ACP) and watershed management plans.

BMP Mechanisms and Processes

A structural BMP facilitates different physicochemical and biological processes to capture stormwater and remove contaminants. These processes include, but are not limited to, infiltration, sedimentation, filtration, sorption, ion-exchange, oxidation/reduction, biodegradation, and phytoremediation (Scholes et al. 2008). However, these mechanisms and processes are not well-understood and certainly not well-quantified within the context of BMPs. Research within this portion of the conceptual model aims to quantify the removal processes of various pollutants for different BMP treatment mechanisms. While multiple processes invariably operate simultaneously within a BMP, these processes are neither uniformly dominant in a specific BMP nor equal in terms of their efficacy for removing a specific contaminant. Relative ranking of these processes in terms of their effectiveness for removing different contaminants would greatly inform BMP screening/selection process when addressing a specific management challenge in a watershed.

BMP Design Criteria

Even when the mechanisms and processes within a BMP are well-understood, BMP solutions need to be tailored to local climate and geologic conditions. These local conditions are the drivers that force BMP design parameterization. This can only be accomplished by field-validating stormwater BMPs to understand all of the "real-life" factors that influence performance. Moreover, field validation needs to occur for both structural as well as non-structural stormwater BMPs. The research for this portion of the conceptual model culminates with development of robust decision support tools that facilitate selection of the appropriate BMP (or set of BMPs) for conditions at a specific geographical location and/or development project. However, this research is perpetually challenged by the vast number of treatment process and mechanism combinations, multiplied by the nearly limitless number of environmental settings in which BMPs can be placed.

Optimizing Long-Term BMP Performance Through Monitoring and Maintenance

Success of a BMP implementation program greatly depends on controlled operation and proper maintenance for the different components of stormwater BMPs. Obtaining information on how well BMPs perform and how best to maintain them is best gleaned through prolonged field testing and validation. However, recent inventories of BMP monitoring data in California reveal a dramatic lack of performance data for many BMPs; data are especially lean if a manager wishes to focus on the BMP's specific environmental setting. The problem of insufficient guidance due to a lack of data is particularly pronounced for maintenance. Many BMP installations are rarely revisited after construction; thus, existing assumptions about their future performance are likely inaccurate. Equally challenging is the ability to demonstrate the effectiveness of non-structural BMPs. While less information is needed regarding engineering design, BMP performance and ongoing effectiveness still need to be monitored for non-structural BMPs, as these assessments ensure that programmatic actions are meeting the needs of watershed management programs.

Optimizing Alternative Compliance Pathways (ACP) and Watershed Management Plans

This portion of the conceptual model relates BMP investment to expected improvements in receiving water beneficial uses. Managers continually push for cost-efficiency in their BMP or BMP network implementation. Thus, research in this area focuses on a comprehensive framework that can compare different BMPs side by side to understand their relative estimated cost/benefit throughout their lifecycle.

Effects

Stormwater Capture: Many municipalities in California depend on imported water to meet increasing water demand due to population growth and land use changes. As regulations surrounding stormwater discharge become more stringent and access to external sources for importing water becomes less reliable and more competitive, urban stormwater is gaining traction as an alternative source of water supply among cities across California. To facilitate this intended beneficial use (e.g., non-potable use, indirect potable use, direct potable use), stormwater BMPs must be properly planned, designed, operated and maintained. Moreover, the link between stormwater infiltration (as opposed to surface runoff) has competing effects that integrate with the hydrology portion of the conceptual plan. Infiltrating stormwater can have positive effects on minimizing peak flows and reducing associated impacts such as erosion. However, infiltrating stormwater can also starve a stream of the stormwater volume and timing necessary to support healthy biological communities.

Receiving Water Responses: One of the primary goals of every watershed management plan is to protect, restore, and maintain receiving water beneficial uses, such as aquatic life. However, region-wide receiving water monitoring consistently demonstrates that aquatic life is widely impacted in urban streams (Mazor et al. 2016). This research area attempts to link BMPs to stream hydrology, chemistry, physical habitat, and aquatic life. In this way, managers can understand how stormwater management practices – such as implementing stormwater and non-stormwater BMPs – relate to receiving water responses. This critical link is perhaps the "holy grail" of runoff management. Once the link is established, stormwater managers can focus on implementing the most effective BMPs at the appropriate level of effort, establishing the value of all prior work.

Research Directions

As regulations such as total maximum daily loads (TMDL) and municipal separate storm sewer system (MS4) permits are developed to improve runoff water quality, environmental managers are turning to stormwater science to inform the most optimal paths forward. SCCWRP is building on decades of past work aimed at understanding the sources and fates of runoff to develop science-informed strategies and tools – especially stormwater BMPs – that optimally meet these current and future water-quality management challenges.

Pollutant Sources

Accomplishments

SCCWRP has been generating pollutant load information since the early 1970s for a variety of sources, including stormwater (SCCWRP 1973, Schafer et al. 1988, Cross et al. 1993, Schiff 1997, Ackerman and Schiff 2003). Over time, pollutant loads from stormwater have increased in response to a growing population and expansion of urban development. This led SCCWRP to complete a series of stormwater pollutant source-related research projects for a wide variety of contaminants, including suspended solids, nutrients, bacteria, trace metals, PAHs and pesticides. These studies developed pollutant source area concepts, such as event mean concentrations (EMCs) to identify the largest pollutant sources, as well as pollutograph monitoring that defined the factors influencing pollutant loading variability, such as build up-wash off, first flush vs. seasonal flush, and optimized stormwater pollutant and BMP monitoring designs (Schiff and Tiefenthaler 2011, Tiefenthaler et al. 2011, Tiefenthaler et al. 2008, Stein et al. 2006, Schiff and Sutula 2004, Leecaster et al. 2002, Schiff et al. 2016). These studies also have focused on source tracking and attribution for non-stormwater inputs, including inputs relative to other point sources (Ackerman et al. 2003, 2005).

Priorities for Future Research

***Future research*: Updating event mean concentrations for Southern California Land Uses**

SCCWRP's previous research on pollutant sources has been foundational in southern California. The event mean concentrations (EMCs) developed by SCCWRP circa the year 2000 have been used in watershed modeling and Water Quality Planning documents by nearly every municipality in the region. However, this work is now more than 10 to 15 years old, and most stormwater managers expect that land use-associated concentrations have changed over time, especially as building codes (including stormwater management measures) have been updated. Also, ongoing non-structural BMPs such as street sweeping, solid waste management (i.e., recycling), and public education have potentially altered land use pollutant loads. This research will repeat many of the studies conducted 15 years ago, generating pollutographs for a variety of pollutants from a range of land uses. In turn, these data will be used for assessing watershed-wide pollutant loads, prioritizing source areas for management measures, and estimating pollutant concentrations entering BMPs for treatment.

Watershed Processes

Accomplishments

For more than two decades, SCCWRP has been researching watershed processes as a precursor to developing effective watershed management strategies. To comprehend where BMP intervention would be most effective and efficient for minimizing human impacts, SCCWRP first needed to understand natural sources and cycles. To that end, SCCWRP invested in research on natural precipitation and climate variability (Ackerman and Schiff 2003, Ackerman and Weisberg 2003, Schiff et al. 2016), as well as natural sources and background levels of pollutants (Schiff and Tiefenthaler 2001, Stein and Yoon 2008, Yoon and Stein 2008, Howard et al. 2014, Griffith et al. 2010). Because accurate and precise models are the primary mechanism for assuring that BMP implementation strategies will ultimately be effective, SCCWRP led regional research into watershed model development, including testing, calibrating and validating the watershed models that are still in use today for long-term planning and decision-making (Ackerman et al. 2005, Ackerman and Weisberg 2006, Ackerman and Schiff 2003, Ackerman and Stein 2008a, Ackerman and Stein 2008b, Sengupta et al. 2018). Finally, SCCWRP investigated the many complex interactions in watershed processes, including interactions across different media (e.g., air-to-surface water, surface water-to-groundwater). SCCWRP research showed that especially in highly urbanized locations like southern California, many stormwater contaminants originate from contaminants that are deposited on land from air during dry periods between storms (Lu et al. 2003, Lim et al. 2006, Sabin et al. 2006, Sabin et al. 2010). In fact, dry atmospheric deposition and subsequent washoff during storm events can make up most of the contaminant mass found in stormwater (Sabin et al. 2005), and this has not changed in many decades (Sabin and Schiff 2008).

Priorities for Future Research

***Future research*: Surface water-groundwater interactions**

While SCCWRP has researched air-stormwater interactions more than perhaps anywhere else in the country, stormwater-groundwater interactions for BMPs remain largely a mystery. This is particularly problematic because many watershed managers emphasize stormwater infiltration as the preferred BMP for reducing volume and pollutant loads, and also storing water underground for future use, including human uses. Except for some isolated studies in southern California (Dallman and Spongberg 2011), the fate and transport of infiltrated stormwater in this region is not well-understood. Research in this area will focus on volumetric infiltration for multi-benefit quantification, such as bolstering groundwater supplies or supplementing baseflow in streams, both of which have been lost as “hardened” urban land uses have decreased much of watersheds’ natural perviousness. Equally important, contaminant transport into subsurface waters from infiltration BMPs will be a focal point of study, as this transport can alter groundwater quality significantly and complicate the multiple benefits promised with infiltration practices.

***Future research*: Updated watershed modeling**

Since SCCWRP researchers first calibrated and validated watershed models for use in southern California in the early 2000s, member agencies and their consultants have been using these models for long-term watershed management planning. Now, as planning transitions to implementation, the limitations of the models are coming into sharp focus. Thus, future research in this area will focus on upgrading the watershed models currently in use and creating additional capabilities specific to needs that were unforeseen 15 years ago. These additional capabilities include updated process rate functions, re-evaluating boundary conditions with new data and technology, and incorporation of additional applications such as mechanistic BMP performance.

BMP Intervention

Accomplishments

SCCWRP has conducted multiple research projects focused on BMP performance assessments, including a comparison of pollutant concentration and load reduction among 12 different structural BMPs for over 100 different pollutants (Schiff and Brown 2015), treatment effectiveness of wetlands (Sutula et al. 2008), and low impact development (LID) BMPs (Peng et al. 2016), as well several structural BMPs focused on reducing aquatic toxicity (Brown and Bay 2005). In addition, SCCWRP has examined the effectiveness of non-structural BMPs, including public education, residential runoff irrigation reduction, and parking lot cleaning (MWDOC and IRWD 2006, Greenstein et al. 2004, Schiff et al. 2016). Finally, SCCWRP has completed multiple projects focused on BMP design, including differential treatment of pollutants sorbed to various size stormwater particles (Brown et al. 2013), optimized BMP placement within watersheds (Ackerman and Stein 2008), and evaluations of optimal design storm criteria for different storm sizes in different locations and climate conditions (Schiff et al. 2007).

Ongoing Research and Priorities for Future Research

BMP Mechanisms and Processes

***Current project*: Quantifying relative significance of various treatment processes in a BMP**

Understanding the mechanisms of stormwater contaminant removal within a BMP is key to developing successful and reproducible contaminant BMP remediation strategies. Fate and transport of contaminants in a stormwater BMPs involves multiple processes, such as infiltration, sedimentation, filtration, sorption, ion-exchange, oxidation/reduction, biodegradation and phytoremediation, among others. These processes need to be balanced against competing physical factors, such as porosity, permeability and hydraulic conductivity. To properly select and design a BMP that is the most effective for a given contaminant or suite of contaminants, scientists and engineers must fully understand these processes in the context of different climate, environmental, and biogeochemical factors (e.g., soil media type, natural and engineered colloids, microbes). This project is examining these processes under controlled laboratory conditions, where each of these processes (or combinations of processes) can be isolated and measured in detail.

***Current project*: Developing and testing novel BMP technology**
Although stormwater regulation began in earnest during the 1990s, BMP technologies to address these regulations are still in the early stages of development. However, stormwater BMP technology is evolving rapidly. For example, the paradigm shift to green infrastructure (i.e., low-impact development, or LID) has gained most of its momentum in just the past decade. As stormwater practitioners and managers work to overcome seemingly insurmountable water-quality treatment hurdles, promising new technologies are emerging. SCCWRP is evaluating the performance of these new technologies, especially as it pertains to their stated promise of improved treatment with longer lifespans at lower costs. SCCWRP is particularly interested in testing new technologies developed – both in house and by others – that are environmentally sustainable, deliver predictable and consistent pollutant reduction, and provide attractive *in-situ* regeneration or retrofit techniques. One such example is biochar, an emerging new biofilter media, which appears to sorb pollutants better than currently used biofilter media, and also offers improved permeability and lifespan.

***Future research*: Investigating effects of design factors on treatment performance**
Most BMP designs that have been implemented in southern California for pollutant reduction have been focused almost entirely on volume capture. This is not a flaw in the current design manuals, but rather a reflection of the incomplete knowledge on BMP mechanisms and processes for contaminant removal (see previous project). The aim of this research project is to optimize the relevant design attributes (e.g., infiltration rates, filter media types and properties, plant pallet) and establish consensus on the best BMP configuration(s) for pollutant treatment as well as volume reduction.

BMP Design Criteria

***Current project*: Evaluating field performance of structural BMPs**
Nothing can mimic real life and, while mechanisms and processes are best quantified using controlled laboratory studies, field-scale BMP performance measurements are essential to evaluating performance of structural BMPs. This project is focusing on quantifying BMP performance data in field deployments to validate laboratory tests and ensure BMP planning and specifications meet predicted outcomes. Field validation of BMP designs is challenging because differences between predictions and real life can be attributed to many factors,

including variability in hydraulic and/or pollutant loading rates, durations of BMP evaluation, BMP footprint, and specific site conditions (e.g., soil type, depth of groundwater table, climatic factors), and proper installation. These challenges are in addition to traditional stormwater monitoring hurdles (e.g., large swings in precipitation, orders of magnitude ranges in water quality during a storm event, and technology limits for monitoring flow). Thus, compiling results from many storm events as measured by SCCWRP or others is essential in refining and validating BMP design specifications. Ultimately, managers need confidence that implementing BMPs will achieve their watershed management goals.

***Future research*: Developing site-specific design criteria**

Stormwater BMP designs tailored to local needs and conditions ensure cost-effective BMP intervention. Fundamental understanding of BMP processes and field-scale testing of BMP performances lay out the foundation for developing a BMP design tool based on site conditions and constraints. Once scientists and engineers have the information on how to optimize BMP design for pollutant reduction and how a specific BMP performs at a specific site (i.e., site conditions, climate), a tool can be developed to quickly translate which design attributes should be used for different pollutants or combination of pollutants. Such decision support systems may include a flowchart or algorithm where managers can input design objectives, site conditions, and historical pre-construction monitoring data to obtain a list of candidates BMP(s) with respectively optimized design attributes.

***Future research*: Evaluating field performance of non-structural BMPs**

Virtually every watershed management plan in southern California relies upon non-structural BMPs to achieve some or all its long-term watershed management goals, including restoring and/or maintaining beneficial uses. Non-structural BMPs include source control (e.g., ordinances, commercial limitation), programmatic activities (e.g., street sweeping, inspections, enforcement), and public education. Despite the reliance on non-structural BMPs, little research has been conducted to quantify their effectiveness. Although much of this research has focused on street sweeping, ongoing monitoring of its effectiveness is non-existent. Limited examples of source control also exist in the literature (e.g., removing lead from gasoline), but source identification studies for many pollutants in stormwater are generally lacking. Finally, the least amount of research has focused on public education and, even in cases where limited data exist, public education has not been very effective at changing public behavior toward improved water quality. The impacts of public education – in terms of its ability to improve discharge and receiving water quality – also are difficult to quantify. This research area will better quantify pollutant reductions associated with non-structural BMPs and provide recommendations for optimizing these activities.

Optimizing Long-Term BMP Performance Through Monitoring and Maintenance

***Future research*: Establishing a BMP performance monitoring framework**

Although stormwater managers have prepared watershed management plans and implemented BMPs, there is an abysmal lack of BMP performance monitoring data to evaluate whether a BMP is performing up to its design goal and/or whether its effectiveness is being influenced by its age. This research project will focus on how to assess performance and monitoring program design. First, there is no standard to assess how well a BMP is performing. Percent reduction, effluent concentrations, and influent-effluent regressions are all approaches used in the literature, but stormwater practitioners have not agreed on the best standardized approach(es) for determining whether a BMP is "working." Not surprisingly, stormwater managers have developed a wide range of approaches for conducting post-construction BMP monitoring. SCCWRP's role in facilitating this science could be key to getting experts to agree on what appropriate metric(s) of BMP performance should be and how to design a model monitoring program for BMP performance. Since every stormwater management agency in southern California is dependent upon BMP performance information – whether they be a regulated or regulatory agency – a regional monitoring program could be the most effective and cost-efficient approach to achieving standardized monitoring for a large number of BMPs under a wide variety of watershed conditions.

***Future research*: Creating a data sharing platform for BMP monitoring data**

Once scientists and engineers reach agreement on how to assess BMP performance, and a standardized monitoring program is created to make these assessment calculations, the next step is to compile and share this information across stormwater management agencies on a data-sharing platform. The platform will be exceptionally useful to practitioners that need to identify the best-performing BMPs in various settings. The platform's collaborative nature will facilitate a high degree of leveraging of data collection efforts. Information technology already exists for creating data portals that allow agencies to submit data, which are then automatically evaluated for quality assurance and seamlessly appended together. These data exploration and visualization tools can be accessed from any web browser, and users can input influent concentrations and estimate effluent concentrations on-the-fly with specified levels of confidence. These tools can be used in design, to verify watershed model parameters, and to estimate probability of achieving successful watershed management goals.

***Future research*: Understanding the effects of operation and maintenance practices on BMP performance**

Stormwater practitioners agree that structural BMPs require maintenance to ensure they are operating at maximum performance. Typical maintenance events for structural BMPs can be categorized as inspection, routine maintenance, restoration, rehabilitation, and retrofit. However, the nature of these activities, required frequency, and cost of maintenance is likely to vary with the type of maintenance events and the type of BMPs concerned. Unfortunately, there are limitd resources established by scientific studies that quantify the benefits of these various maintenance activities and their frequency in terms of BMP effectiveness. Local conditions, management goals, and financial constraints pose further challenges for stormwater practitioners in developing an optimized maintenance protocol. SCCWRP is committed to conducting research on BMP maintenance while the majority of stormwater BMPs constructed in Southern California are still relatively new. The goal is to ultimately develop a guidance document that describes a BMP maintenance protocol optimized for southern California climate and associated management challenges. Such a document would include recommended maintenance activities and maintenance frequency for a wide range of BMPs, as well as minimum reporting parameters to internally track, schedule, and budget ongoing and future maintenance activities.

Optimizing Alternative Compliance Pathways and Watershed Management Plans

***Future project*: Ranking BMP options/arrangements for optimal effectiveness**
Watershed managers rarely rely on a single BMP to remedy water quality problems within their watershed. Instead, they typically opt for a combination or network of non-structural BMPs, large regional structural BMPs, and smaller distributed structural BMPs. The goal of this research area is to optimize how this network of BMPs can be implemented throughout a watershed to achieve watershed management goals. This research encompasses three main factors: BMP effectiveness and longevity, spatial BMP combinations, and BMP costs. BMP effectiveness and longevity were addressed previously (see the two research subthemes above). Thus, this research is focused on BMP placement using dynamic watershed models and updated, site-specific BMP performance information. Additionally, a second focus is on cost – specifically, full lifecycle costs – so that managers can realistically budget long-term capital improvement plans.

***Future research*: Developing a currency for water quality equivalency**
Water quantity and quality trading is controversial, but it is a potential tool for stormwater managers to improve water quality. When building or retrofitting an onsite BMP is infeasible (i.e., no space, no infiltration, etc.) or inordinately expensive, implementation at an off-site BMP can help stormwater permittees attain runoff capture objectives, TMDL targets, or water-quality objectives. However, the trading framework for stormwater BMP implementation is ill-defined and still in its infancy. SCCWRP is interested in developing the technical foundation for a trading market. Technical underpinnings yet to be resolved include developing the “currency” for trading, evaluating the “value” of different BMPs, and quantifying the associated risks and uncertainties with different

trading scenarios. Although SCCWRP is known for its neutral role, SCCWRP is unlikely to become the water quality/quantity trading broker.

Receiving Water Impacts and Stormwater Capture

Accomplishments

For more than two decades, SCCWRP has been researching the role that stormwater discharges have on receiving water impacts. Receiving water impacts fall into three main types: marine habitat quality for aquatic life, freshwater habitat quality for aquatic life, and beach/recreational water quality for human health. All three types of receiving water impacts are addressed in detail within the Bioassessment and Microbial Water Quality research themes, so the focus here is on their relationship to stormwater management and their linkage to stormwater BMPs.

SCCWRP's stormwater research on marine habitat quality has produced a variety of stormwater plume tracking studies (Jones et al. 1996, Schiff et al. 2001, Nezlin et al. 2008) that have documented increased contaminant concentrations in both the water column and sediment (Schiff and Stevenson 1996, Zeng and Vista 1997), aquatic and sediment toxicity (Bay et al. 1996, Jirik et al. 1998, Skinner et al. 1999, Schiff et al. 2001, Bay et al. 1999, Bay et al. 1997), and alterations to biological communities (Bay and Schiff 1997, Schiff et al. 2000). Although these impacts appear worse in estuaries at the mouth of the region's most urbanized watersheds, the impacts have been slowly decreasing since 1998, perhaps because of urban stormwater management measures (Schiff et al. 2015).

Because stormwater impacts might be even worse in freshwater habitats than estuarine habitats, SCCWRP has facilitated regional stream assessments, which have illustrated that most stream-miles in urban watersheds contain biological impacts (Mazor et al. 2016). SCCWRP has worked to identify the most significant stormwater stressors (May et al. 2015) and has developed tools for identifying these impacts (Schiff et al. 2015) helping to focus future management actions, such as implementation of BMPs.

SCCWRP research on bacterial receiving water quality has identified that the vast majority of swimmer warnings occurred near storm drains in dry weather, and that these warnings rapidly spread coast-wide following storm events (Noble et al. 2000, 2003). This led SCCWRP to focus on improving source tracking technology for microbial contamination (Boehm et al. 2013), including writing the State's Microbial Source Tracking Manual (Griffith et al. 2013) to help managers identify where management actions – such as improved source control and BMP implementation – are best applied. SCCWRP also has quantified the health risk of swimming at runoff-contaminated beaches (Arnold et al. 2013, Colford et al. 2012), including during wet weather (Arnold et al. 2017); this epidemiology work has enabled researchers to quantify the levels of microbes that BMPs need to reduce to protect human health (Soller et al. 2017).

Ongoing Research and Priorities for Future Research

***Current project*: Prioritizing flow capture BMPs to restore natural flow regimes**

Restoration of natural flow regimes is an increasingly important component of stormwater management programs. SCCWRP is applying flow-ecology principles to help local stormwater managers achieve appropriate flow regimes for maintaining healthy aquatic life using flow capture BMPs. Given that program managers must decide where to place flow capture BMPs, how much water to retain, and how to time releases back into the receiving streams, SCCWRP is applying the newly developed California Environmental Flows Framework to establish ecologically relevant flow targets for biologically sensitive stream reaches, and to help prioritize how to site and design flow-capture BMPs that can help meet those targets.

***Future research*: Quantifying effects of BMP intervention on changes in receiving water quality**

Stormwater managers are planning to spend billions of dollars on BMP interventions to improve receiving water quality, yet case studies that directly link BMP interventions with improved receiving water quality are extremely rare. This research will establish the elusive link between BMP interventions and receiving water improvements. The lack of demonstrative case studies is at least partly due to the complexities of this linkage, including contributions from non-stormwater pollutant sources, multiple or cumulative stressors not addressed by the BMP intervention, or simply the scale of BMP effectiveness. These complexities are compounded by the large variability in stormwater flow and pollutant concentrations, which can mask real trends in receiving waters. Assessing direct cause-and-effect improvements from BMP interventions are further hindered by complicated ecological interactions, such as biological recruitment or succession. Thus, this project will require large, high-resolution data sets to tease apart natural variability from receiving water change (signal-to-noise ratio). To help ensure receiving water changes can occur, the project will deploy BMP interventions that are aggressive relative to watershed area. One potential avenue for generating such data sets is SCCWRP-facilitated regional monitoring programs (Southern California Bight Regional Monitoring Program and Southern California Stormwater Monitoring Coalition Regional Watershed Monitoring Program), where hundreds of receiving water samples are collected per survey.

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